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# Calibrating a wind turbine model using diverse datasets

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**Abstract.** This paper presents a model calibration investigation using a wide range of available data. The wind turbine under investigation was the V52 research turbine located at Denmark Technical University (DTU) Risø campus. The data included drawings and static and dynamic tests for both the entire wind turbine and the isolated blades. Each set of data was used to calibrate some aspect of the final model. There are three main parts of this paper. First, the different data sources are outlined, including an overview of the experimental procedures and the key results. Second, the model calibration procedure for each set of experimental data is explained. Third, recommendations for the calibration procedure are presented for future researchers and the key outcomes of our calibration investigation are discussed.

## 1. Introduction

The utility of a well-calibrated model<sup>1</sup> is well-known. A “digital twin”, as it is sometimes called, allows us to test a device of interest under many different operational conditions much faster than real time. Moreover, we can subject our digital version of the device to conditions that might cause catastrophic failure in the real world without concerning ourselves with the waste of expensive resources, and we can efficiently run extensive batteries of tests to be certain that design criteria are met. Alternatively, we can use the simulation model to determine which real-world tests have the lowest cost-to-benefit ratio. In short, the calibration of a computer model of a system of interest is an essential step in research investigations related to that system.

Many investigations have been made into the calibration of wind turbine models; however, for brevity, only the most directly relevant works will be discussed in detail here. Of the published papers, some focus primarily on the generator/drivetrain [2, 3, 4], some focus primarily on the blades [5, 6, 7], and some consider the entire turbine system [8, 9, 10, 11]. The two publications that are most relevant to this paper are Griffith *et al.* [7] and Jonkman [11]. In particular, Griffith *et al.* [7] used measurement data from blade static and modal testing to calibrate a blade model, similar to what was done for the blade calibration in this paper. Jonkman [11] used a large amount of experimental data from the Unsteady Aerodynamics Experiment (UAE)

<sup>1</sup> Note the difference between model calibration (i.e., model tuning) and model validation (i.e., testing a model’s predictivity). For brevity, a full discussion of this distinction is not included here. We instead refer the interested reader to Trucano *et al.* [1].



research turbine and created a calibrated model in FAST\_AD, the predecessor to NREL's open-source wind turbine simulator FAST [12], which is similar to this paper's objective of calibrating a HAWC2 model for a research turbine at DTU Risø campus. However, this paper extends beyond the existing literature by using a different blade calibration technique than Griffith *et al.* [7] and by presenting in detail a recommended calibration procedure for a full-system model that includes a few key parameters that are missing in Jonkman [11].

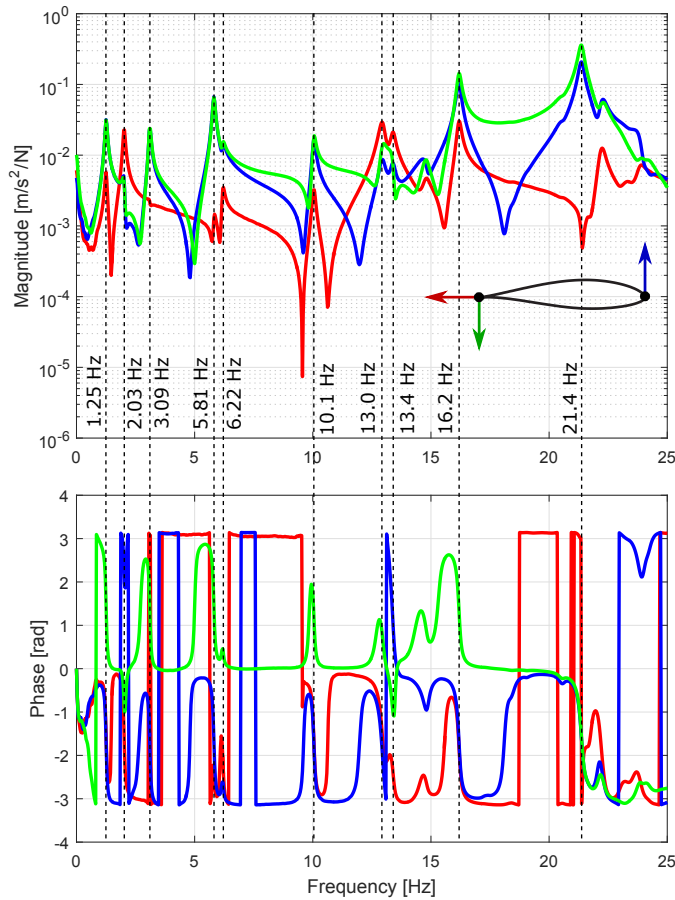
The wind turbine of interest in this paper is the Vestas V52 research turbine located at the Denmark Technical University (DTU) Risø campus. The research turbine features many different instruments and has its own meteorological mast a few dozen meters west of its location. Due to its significant utility in future research investigations, several experiments have been carried out on different parts of the turbine with the goal of creating a HAWC2 [13] model of the turbine. This model will then be used in future validation studies at Risø campus. This paper summarizes the procedure that we followed to calibrate the initial HAWC2 model, including an explanation of the data and drawings that were available as well as a comparison of the simulations with the experimental data. It is hoped that this paper will be useful to future researchers who seek to calibrate wind turbine models based on measurements.

The remainder of the paper is as follows. First, an overview of all experimental data, drawings and other values that were used to calibrate the model is presented in Sec.2. Section 3 contains the calibration procedure for the HAWC2 model as well as comparisons between the simulations and measurements. Section 4 summarizes our significant findings and recommendations for wind turbine model calibration. Finally, the paper is concluded in Sec. 5.

## 2. Calibration data

This section presents an overview of the measurements, drawings and other parameters that were available during the model calibration process. In particular, the following quantities were available to tune the model:

- **FLEX4 model:** The first iteration of the HAWC2 model included parameters taken from a FLEX4 model provided by Vestas. These parameters included distributed structural and aerodynamic properties of the blades as well as lift and drag profiles. These parameters were later modified using other data (see Sec. 3).
- **Tower drawings:** The V52 research turbine is installed on a custom tower with a hub height of 44 m. The original tower drawings were available, and these drawings were used to calculate the distributed tower properties necessary for a HAWC2 model, assuming a conical tower with circular cross-sections. Due to paper-length constraints, this step will not be discussed in detail.
- **Blade drawings:** One blade schematic was available that showed the thickness, chord and twist at different stations along the blade. This drawing also indicated the theoretical total mass of the blade, though this value was superseded by the measured blade mass (see next bullet).
- **Blade mass and center of gravity:** A V52 blade was tested at Risø in the early 2000s, and an accompanying report was published in April of 2003 [14]. A collection of structural tests were performed, including static strength tests with strain gages. Most importantly, the report included the measured mass of the blade (1915 kg) and its center of gravity (7.3 m from the root).
- **Static blade deflection:** A measurement campaign was conducted in 2016 to produce blade deflection data that could be used to validate finite-element models of the V52 blades. Two of the three V52 blades were loaded in multiple configurations, and their resulting deflected shapes were measured at four stations along the blade. The blades were mounted on a test rig with an 8° inclination in the DTU Wind Energy Testing Facility, and then three



**Table 1.** Measured blade mode modal frequencies

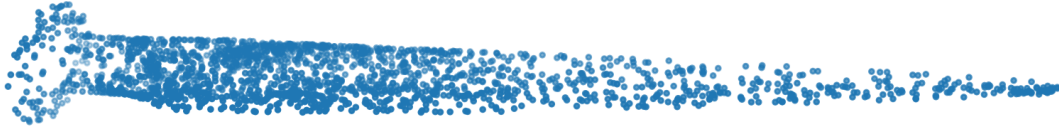
Freq	Mode
1.25 Hz	1st Flapwise
2.03 Hz	1st Edgewise
3.09 Hz	2nd Flapwise
5.81 Hz	3rd Flapwise
6.22 Hz	2nd Edgewise
10.1 Hz	4th Flapwise
13.0 Hz	3rd Edgewise
13.4 Hz	4th Edgewise
16.2 Hz	5th Flapwise
21.4 Hz	1st Torsional

**Figure 1.** Frequency-response function for blade impact-hammer test

tests were conducted: flapwise, flap-torsion, and edgewise. The blades were each mounted for the flapwise and flap-torsion tests such that the chordline for the blade tip was parallel to the ground. The blade was then rotated 90°—so that the leading edge was directed upwards—for the edgewise test. The loading for all three tests was accomplished by slowly winching a heavy concrete block onto a yoke 22 m from the root of the blade. The block was attached to the yoke at the mid-chord. For the flap-torsion test, a smaller load was used to reduce flapwise deflections and the load was offset approximately one meter from the shear centre to induce torsional deflections. The loading configurations are summarised as follows:

- Flapwise: 829 kg along the shear centre
- Flap-torsion: 421 kg offset from the shear centre approximately 1.054 m
- Edgewise: 829 kg along the shear centre

The resulting blade deflections were measured in two directions. First, the deflection in the vertical direction was measured at the leading edge and trailing edge of the blade using wire-drawn transducers at four different stations (5.5 m, 11.0 m, 16.5 m and 21.5 m from the root). These measurements were used to calculate the mid-chord vertical deflection



**Figure 2.** 2000 randomly sampled points from the scan data of Blade A

$\Delta y_{mc}$  and the rotation at that station  $\alpha$  via the following equations:

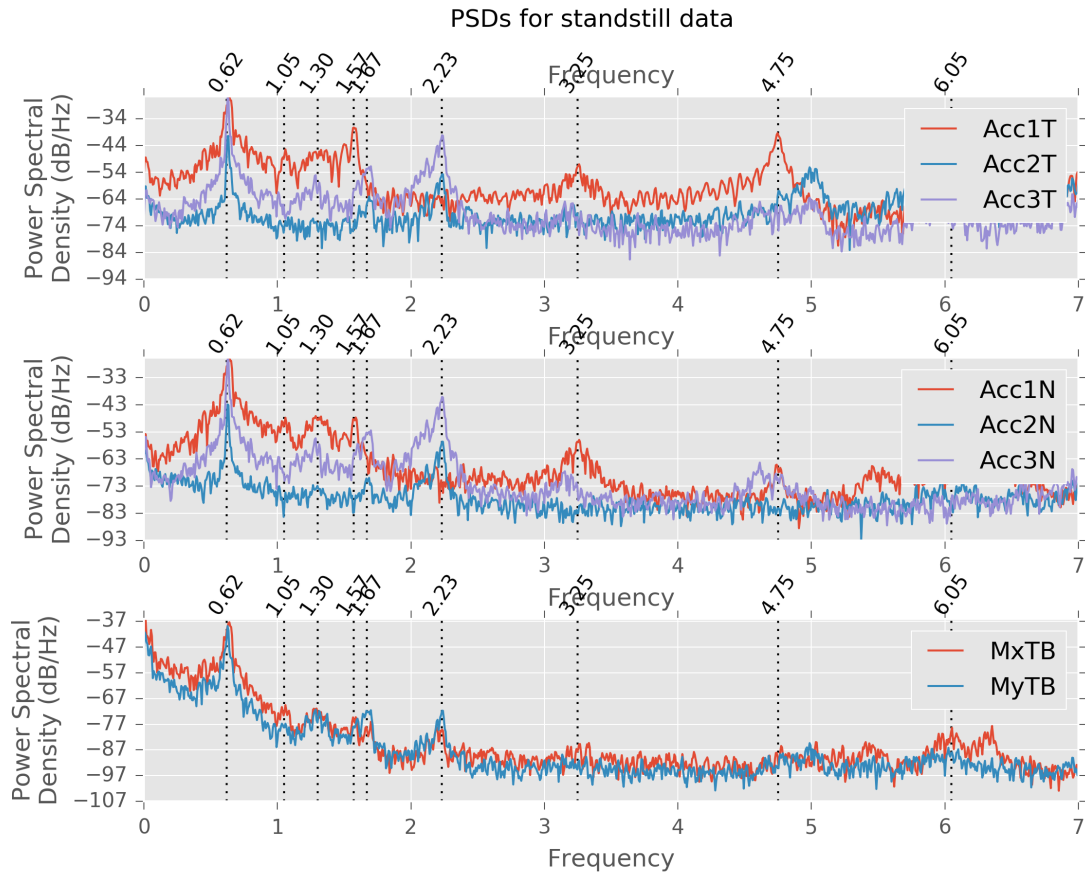
$$\Delta y_{mc} = (\Delta y_{LE} + \Delta y_{TE})/2, \quad \alpha = \text{atan} \left( \frac{\Delta y_{LE} - \Delta y_{TE}}{c} \right) \quad (1)$$

where  $\Delta y_{LE}$  and  $\Delta y_{TE}$  are the vertical deflections at the leading edge and trailing edge, respectively, and  $c$  is the chord at the measurement point. Second, the deflection of the blade in the horizontal direction was measured manually using a ruler and wires hanging from the ceiling of the testing facility. Thus, the measurement campaign resulted in the following quantities measured at four stations (5.5 m, 11.0 m, 16.5 m and 21.5 m from the root) along the blade: flapwise, edgewise and torsional deflection under flapwise loading; flapwise, edgewise and torsional deflection under torsional loading; and flapwise and edgewise deflection under edgewise loading.

- **Blade modal test:** An impact-hammer test was performed on one of the blades when it was mounted on the test rig in the testing facility. The blade had two accelerometers measuring the flapwise acceleration at the leading edge and trailing edge and one measuring the edgewise acceleration at the trailing edge. The resulting frequency-response function is shown in in Fig. 1 along with the identified frequencies. The blade modal frequencies are summarized in Table 1.
- **3D blade scan:** All three blades were subjected to 3D scans before being mounted on the wind turbine. The measurements were available in a text file that listed each 3D coordinate of each scan point. An example scatter plot of 2000 random points is given in Fig. 2.
- **Airfoil coefficients:** The lift and drag coefficients were updated using the NACA profiles published in [15] and results from XFOIL [16].
- **Standstill test:** Full-system natural frequencies were available from a standstill test. The rotor was locked in a “bunny ears” configuration with the blades pitched in the stop position for 65 min and then in the run position for 70 min. Time series were recorded with accelerometers at the tower top and in the nacelle and with strain gages at the tower base. These time series were then used to calculate power-spectral densities (PSDs) of the different channels for each 10-minute period. Ranges of the full-system natural frequencies were identified using these PSDs. An example PSD is given in Fig. 3, and the resulting ranges of the full-system natural frequencies are given in Table 2.

### 3. Model calibration

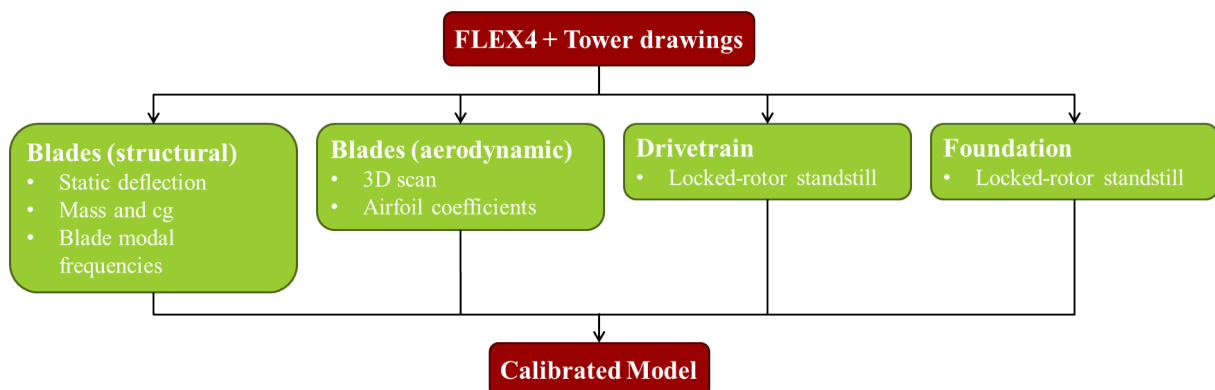
This section describes the calibration procedure for the structural and aerodynamic properties of the HAWC2 model of the V52 research turbine. An overall schematic of the procedure is given in Fig. 4. The initial HAWC2 model was created from the FLEX4 model combined with the distributed tower properties calculated from the design drawings (see Sec. 2). The subsequent calibration procedure can be separated into four groups: blades (structural), blades (aerodynamic), drivetrain and foundation. Each of these groups is discussed in detail in a



**Figure 3.** Example power-spectral density of locked-rotor test

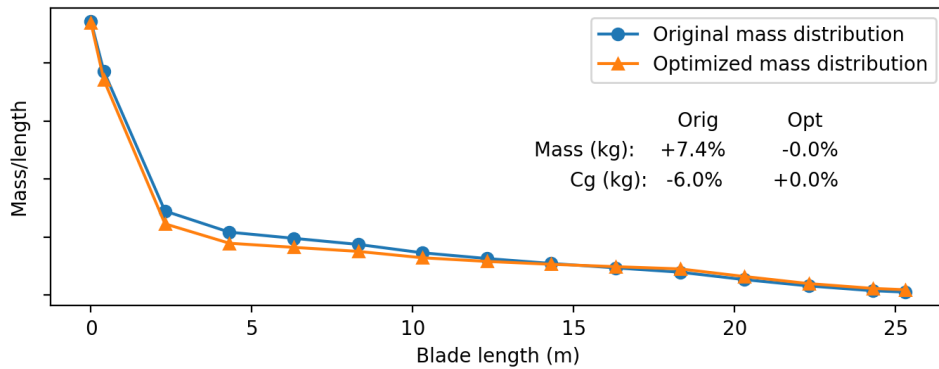
**Table 2.** Ranges of full-system, locked-rotor standstill frequencies extracted from PSDs

Freq (Hz)	Mode	Freq (Hz)	Mode
[0.615, 0.625]	Tower - FA	[2.120, 2.130]	1st Edgewise Vertical
[1.020, 1.050]	Tower - SS	[2.167, 2.187]	1st Edgewise Horizontal
[1.145, 1.155]	1st Flapwise Yaw	[2.780, 2.810]	2nd Flapwise Yaw
[1.170, 1.190]	1st Flapwise Tilt	[2.820, 2.860]	2nd Flapwise Tilt
[1.360, 1.400]	1st Flapwise Symmetric	[3.220, 3.300]	2nd Flapwise Symmetric



**Figure 4.** Schematic of calibration procedure





**Figure 5.** Mass distribution before and after optimisation

dedicated subsection below. Damping was added to the resulting calibrated model by manually adjusting the damping values until desired log decrements for the tower, tower top, shaft, hub and blade components were achieved (2%, 2%, 7%, 2% and 1%, respectively, based on the authors' practical experience with other wind turbine models).

### 3.1. Blades (structural)

The distributed structural properties of the blades were calibrated in three steps. In the first step, the mass distribution was optimized such that the total mass and center of gravity of the blade model matched the measured values given in Sec. 2. In the second step, the distributed edgewise and flapwise stiffnesses of the blades were manually changed until the simulated static deflected shapes and blade modal frequencies matched the measured values. In the third step, the blade torsional stiffness was scaled such that the simulated and measured rotations under torsional loading matched. The mass and stiffness (flapwise, edgewise and torsional) optimisations are discussed in respective subsections below.

**3.1.1. Mass-distribution optimisation** The blade mass distribution was calibrated by solving the following optimisation problem:

$$\min_{m_i} \left[ \frac{m - m_{msmt}}{m_{msmt}} \right]^2 + 2 \left[ \frac{c_g - c_{g,msmt}}{c_{g,msmt}} \right]^2 \quad (2)$$

Here, subscript  $i$  indicates that we are optimising the mass-per-unit-length value at each of the stations shown in Fig. 5; subscript  $msmt$  indicates the measured value of a parameter;  $m$  indicates the total mass of the blade; and  $c_g$  represents the center of mass of the blade. The center of gravity of the blade was determined to be more important than the total mass of the blade, so it was given an increased weight in the cost function.

The optimisation problem was solved in Python using the Sequential Least Squares Programming solver in SciPy. To speed up the problem and to ensure that the resulting mass distribution did not vary significantly from the original mass distribution, bounds were implemented such that the mass distribution did not change more than 20% of its original value or decrease below 4 kg/m. The resulting mass distribution (shown in Fig. 5) had a total mass and center of gravity that matched the measured values (i.e., 1915 kg and 7.3 m) out to five decimal places.



*3.1.2. Stiffness-distribution optimisation* The tuning of the distributed blade stiffness properties was by far the most complicated aspect of the model calibration. There were two main steps: tuning the flapwise and edgewise stiffnesses and tuning the torsional stiffness. Both steps utilised a HAWC2 model that simulated the static deflection tests, including the test rig. The torsional stiffness tuning was fairly straightforward: the shear modulus  $G$  was scaled equally at all sections until the simulated flap-torsion rotations overlaid the measured rotations (a decrease in  $G$  from 20 GPa to 18.6 GPa, about 7%). The flapwise/edgewise tuning procedure was more involved and is therefore discussed in detail below.

The distributed flapwise and edgewise blade stiffnesses were tuned by manually determining the values of ten design variables, each of which represented a percent scaling of either the flapwise or edgewise area moment of inertia at one of five possible sections: 0 to 5.5 m, 5.5 to 11 m, 11 to 16.5 m, 16.5 to 21.5 m or 21.5 m to 25.3 m, all measured from the blade root. These sections correspond to the sections defined by the measurement locations during the deflection test. Different values of the percent scalings of the edgewise and flapwise stiffnesses in these sections were tried until the simulated static deflection test and blade modal frequencies matched the measurements to a sufficient degree of accuracy. In the end, the following scalings were obtained:

Section	0–5.5 m	5.5–11 m	11–16.5 m	16.5–21.5 m	21.5–25.3 m
Flapwise	+4.87%	+26.86%	+36.34%	+4.87%	+25.85%
Edgewise	-25.97%	+5.75%	+48.05%	+16.32%	+37.47%

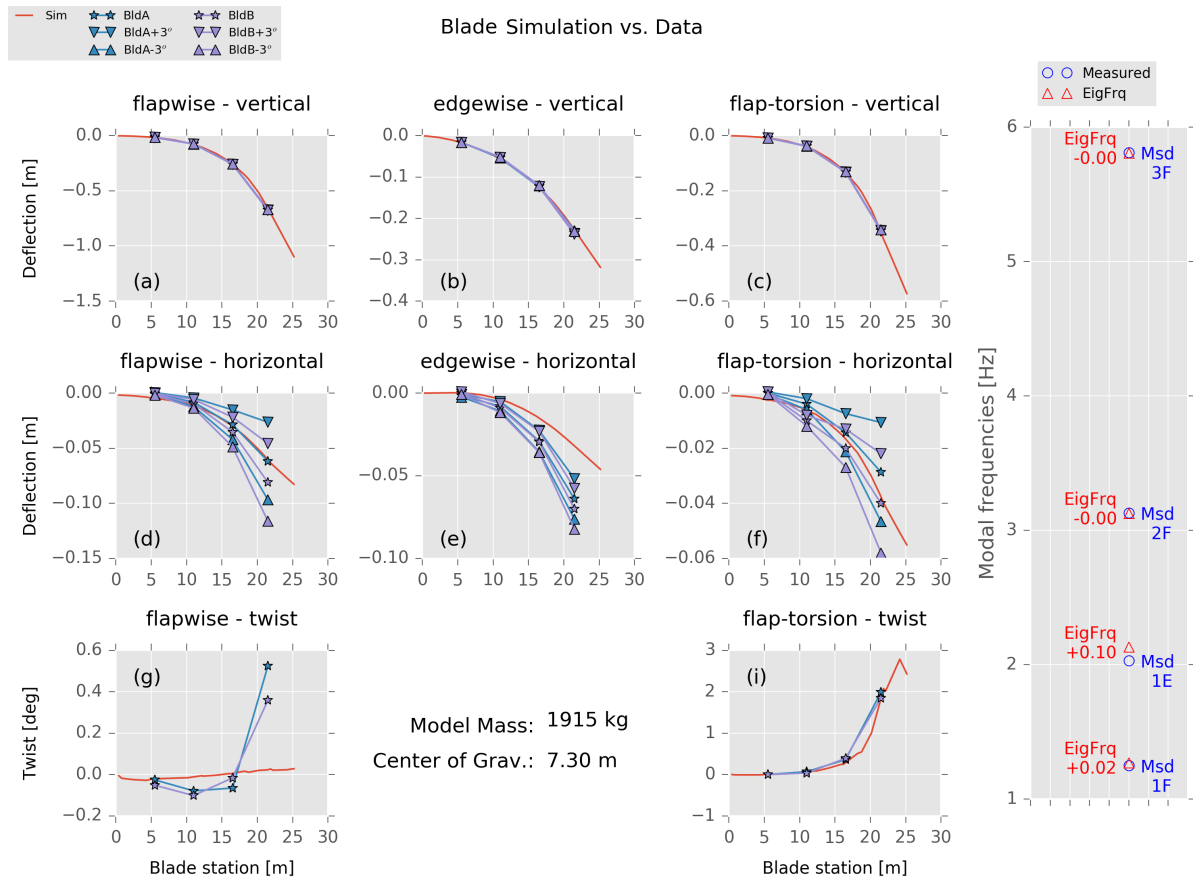
The comparison of the simulated and measured static blade deflection and the first four modal frequencies is shown in Fig. 6. As can be seen in the figure, the deflections in the vertical direction (top row) match quite closely for all three tests. There is some difference in the horizontal deflections and in the torsional deflection for the flapwise test. These discrepancies could possibly due to the less-accurate measuring method in the horizontal direction or due to the assumption that the shear center coincided with half-chord point. However, we elected to focus primarily on the vertical deflections and modal frequencies, which also match extremely well, so this difference in the horizontal deflections is not further addressed. Lastly, the first four blade eigenfrequencies match the measured blade modal frequencies extremely well, with a largest discrepancy of 0.10 Hz occurring in the first edgewise mode. Thus, the structural properties of the simulated blade can be concluded to mimic those of the actual blade to a good degree of accuracy.

### 3.2. Blades (aerodynamic)

The aerodynamic properties of the blades were calibrated in two ways. First, the lift and drag curves were replaced with a combination of measured profiles from [15] and curves calculated in-house using XFOIL [16]. Second, the distributed values for the thickness, chord, twist and offset were updated using the 3D scan data. The 3D scan data was separated into different stations, and at each station the following procedure was applied:

- (i) Convert the scan data to polar coordinates
- (ii) Identify the leading edge and trailing edge by picking out the two maximal points that are at least  $\pi/2$  rad apart
- (iii) Use geometrical relationships to determine the section's chord, twist and offset (according to HAWC2's blade-model formulation) from the leading edge and trailing edge points
- (iv) Transform the airfoil such that it has no twist or offset
- (v) Determine the thickness from the maximum and minimum points in this transformed space

A demonstration of this procedure is shown in Fig. 7, and a comparison of a fit airfoil to scan data is shown in Fig. 8. The resulting curves for the thickness, curve, twist and horizontal



**Figure 6.** Schematic of calibration procedure

offset were similar to those from the FLEX4 model except near the root of the blade, but the vertical offset values differed quite substantially (curves not shown for proprietary reasons). The overlays of the transformed airfoils with the scan data indicated good agreement between the obtained curves and the physical blade characteristics.

### 3.3. Drivetrain

The drivetrain torsional stiffness was tuned by changing the shaft's polar moment area of inertia until the simulated frequency for the 1st Edgewise Horizontal mode matched the measured value.

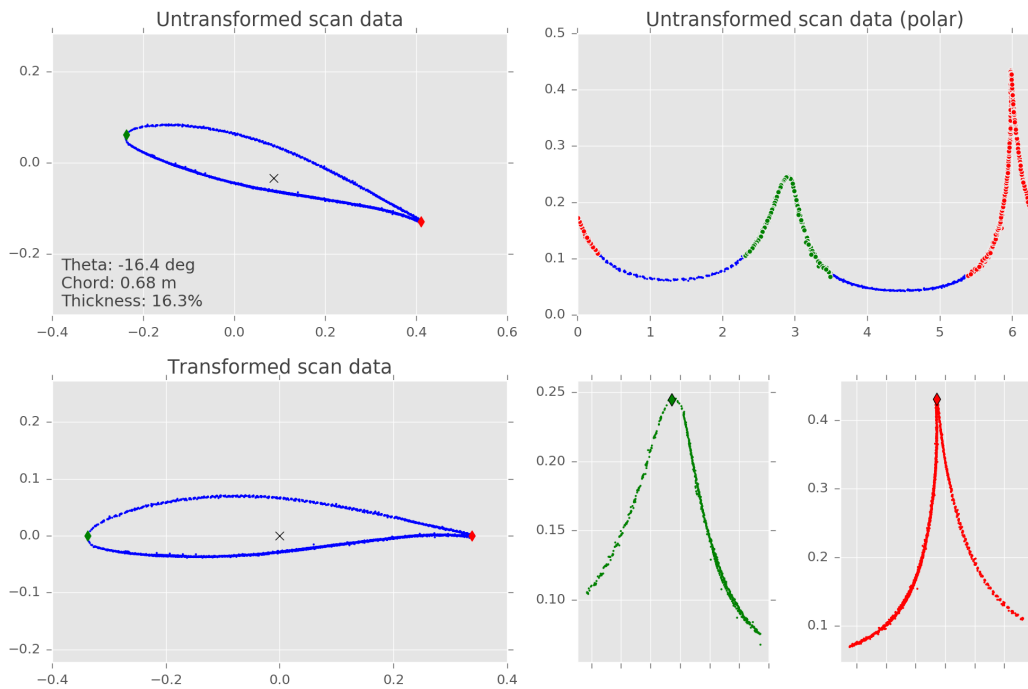
### 3.4. Foundation

The foundation stiffness was tuned by changing the foundation's Young's modulus until the simulated frequency for the fore-aft tower mode matched the measured value. The foundation was the last step in the calibration procedure before damping was added (see beginning of section).

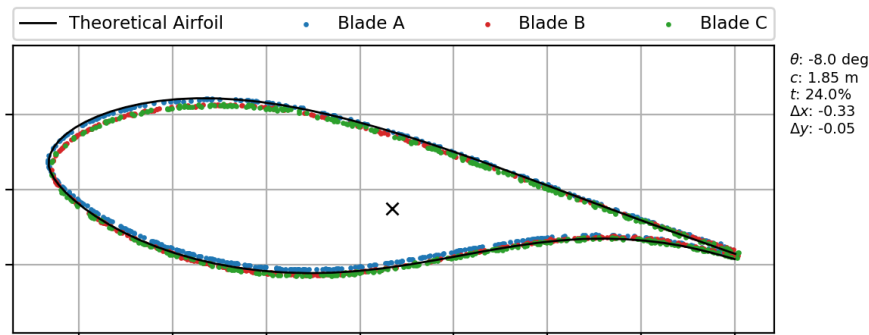
## 4. Observations and recommendations

Based on our experiences with this calibration procedure, we present the following observations and recommendations:

- *Decouple blade mass/stiffness tuning:* The blade mass can be calibrated based on the



**Figure 7.** Demonstration of determining the thickness, chord, twist and offset from the scan data



**Figure 8.** Comparison of airfoil with fit thickness, chord, etc. to scan data

expected total blade mass and center of gravity, as discussed above. Then, the blade stiffness can be calibrated using static deflection tests, pull tests and/or modal tests.

- *Blade stiffness tuning is most involved:* The tuning of the blade stiffness to the deflection test and modal test data was by far the most complicated aspect of the calibration procedure.
- *Extract distributed aerodynamic properties from blade scan data:* Our results indicate that it is quite easy to obtain high-quality estimates of the distributed chord, thickness, etc., from 3D scan data. Comparisons of the theoretical airfoils to the blade scan also allowed us to determine how well the scheduled airfoils matched the actual blade profile.
- *Determine drivetrain and foundation stiffness from standstill tests:* The foundation stiffness can be tuned from the first full-system mode during non-operation. The drivetrain stiffness

requires a locked-rotor test.

- *Calibrate blades first:* We recommend first calibrating the structural and aerodynamic properties of the blades before moving onto other aspects of the turbine.

## 5. Conclusions

This paper presents observations and recommendations based on the calibration of a HAWC2 model of the V52 research turbine located at DTU Wind Energy Risø campus. The model was calibrated using a diverse set of data sources that included blade measurements and full-system measurements, amongst others. The calibration of the structural and aerodynamic properties of the blades, the drivetrain and the foundation is discussed in detail, and our recommendations for wind turbine model calibration are summarised. It is hoped that the information presented in this paper will be useful to other researchers performing similar calibrations in future works.

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